Scanning LDV measurement technology for vibration fatigue testing

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ABSTRACT

Vibration fatigue testing is a verification method for structural components. It is rapid and cost efficient, and it is often performed for aero-engine components because it replicates closely stresses under normal operation conditions. This testing methodology is well known for metallic components but it can also be applied to composites for studying failure caused by high cycle fatigue. Resonant frequency decay is usually the main parameter used to assess fatigue behaviour of metallic components at a given excitation level. However for composites this alone is not very useful and several measurement parameters need to be monitored in order to understand the behaviour and develop a set of failure criteria. Scanning LDV is an excellent measurement system which enables a variety of options thanks to its non-contact nature. This manuscript will show how this system can be used for monitoring several parameters during vibration fatigue testing. A custom made control panel called MONTEVERDI and the independent use of the scanning mirrors allow the SLDV to perform several tasks: (i) Phase Lock Loop (PLL) to excite the component always at resonance, (ii) measuring of Operational Deflection Shape (ODS) using either step or continuous scanning method, (iii) custom calibrated strain measurement and (iv) phase portrait for nonlinear vibration analysis. This paper will present the great potential of using SLDV for performing time consuming vibration fatigue testing via an automated control panel.

Keywords: Scanning Laser Doppler Velocimeter, automated testing, vibration fatigue, Operative Deflection Shape

1 INTRODUCTION

Vibration fatigue is a testing technique that allows a rapid and cost-efficient evaluation of the fatigue life of a component. It consists of exciting a structure by an excitation force at any resonance frequency, causing the structure to respond according to its dynamic characteristics. This method closely replicates the operational conditions of components undergoing vibratory stresses, allowing high excitation levels with relatively low input power.

Vibration fatigue testing is well standardized for metals. It was developed during the 50's [1]–[3] by Lazan et al. and it consisted in exciting a specimen around its resonant frequency by rotating an eccentric mass. The vibration amplitude was fed back to the controller thanks to an accelerometer mounted on the top of the specimen grip. In spite the reliability of accelerometers, sometimes there is a need of non-contact sensor for measuring vibration amplitude without interfering with the system response. Non-contact control systems rely on either video extensometer sensors or laser triangulation sensors [4], with the drawback of being dedicated to measure the vibration of a single point.

This manuscript shows how to carry out an automated fatigue test to characterise the fatigue behaviour of composite components using a Scanning Laser Doppler Velocimeter (SLDV) system. The SLDV system is used (i) for performing both an amplitude and a phase lock loop control, (ii) for calibrating the displacement with the relative strain and (iii) for measuring important dynamic parameters such as nonlinearities in the vibration and ODS.

2 MATERIAL AND METHODS

The test setup used here consists of a component which is excited at its first bending mode, clamped within the two rods of a steel fixture, and attached to the head of a shaker (see Figure 1). As shown in Figure 2, the component is a rectangular specimen, 100 mm wide and 260 mm long, with an added weight at 50 mm away from one edge, clamped at 110 mm and with ply drops in the centreline, at 130 mm. By adding the ply-drop, the component is forced to break in a desired location, along a line, away from the clamp.

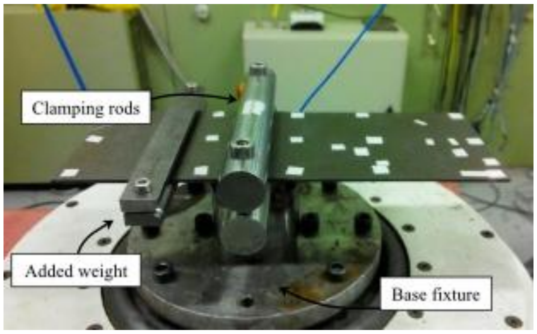


Figure 1 - Fixture set-up

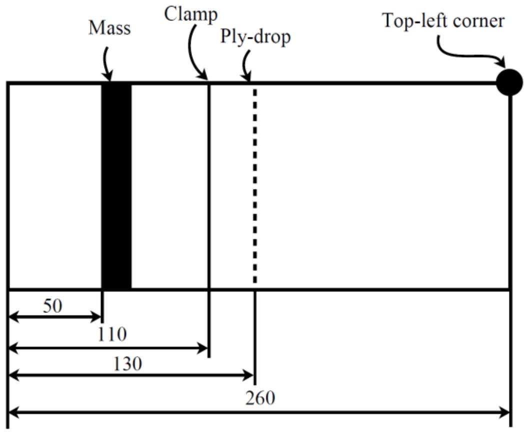


Figure 2 – Specimen dimensions

MONTEVERDI software, coded in LabVIEW, was specifically designed to automate the fatigue tests and used for this research work. The flowchart in Figure 3 shows the entire test procedure, from the modal test to the endurance test. The software is made to perform a series of operations including Frequency Response Function (FRF), Stepped Sine Test (SST), calibration of strain-amplitude relationship, thermal imagining and endurance test. One accelerometer, attached at the fixture, was chosen for referencing the FRF and for the Phase Lock Loop (PLL) control during the fatigue test.

The steps reported in Figure 3 are required to study the dynamic behaviour of the system before, during and after the fatigue test. First of all the response of the structure is measured so as to identify the response target mode. After the first bending mode is identified, the stepped sine test is carried out at different vibration levels. In addition the strain-displacement calibration is made. This practice is adopted because the extreme dynamic environment, which either (i) forces the strain gauges to peel off from the specimen and/or (ii) fatigues the cable after few thousands cycles. To overcome such an issue, the strain and the LDV output signal are synchronously measured, as shown in Figure 4a. The measured data are then correlated and a linear calibration curve is obtained as in Figure 4b. As long as the mode shape does not change and the resonance frequency does not change, it is fair to consider the strain amplitude relationship constant throughout the test.

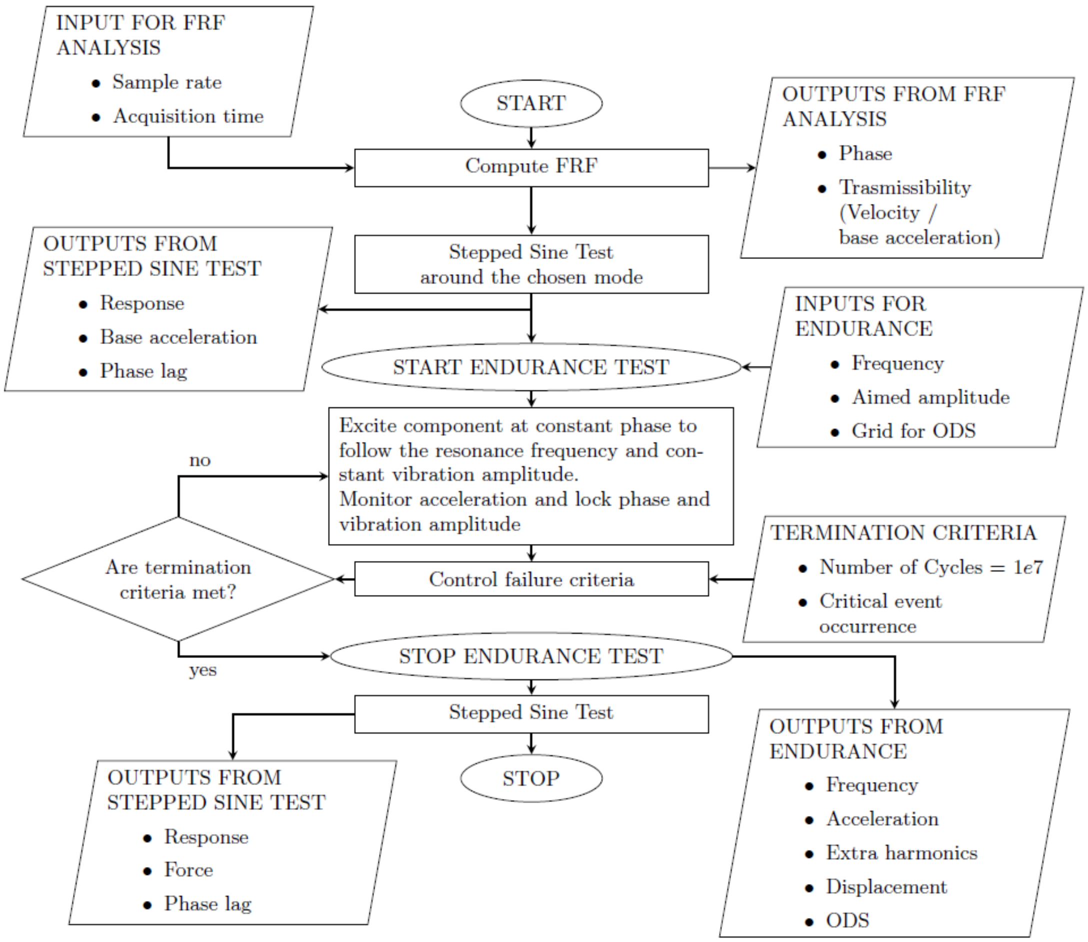
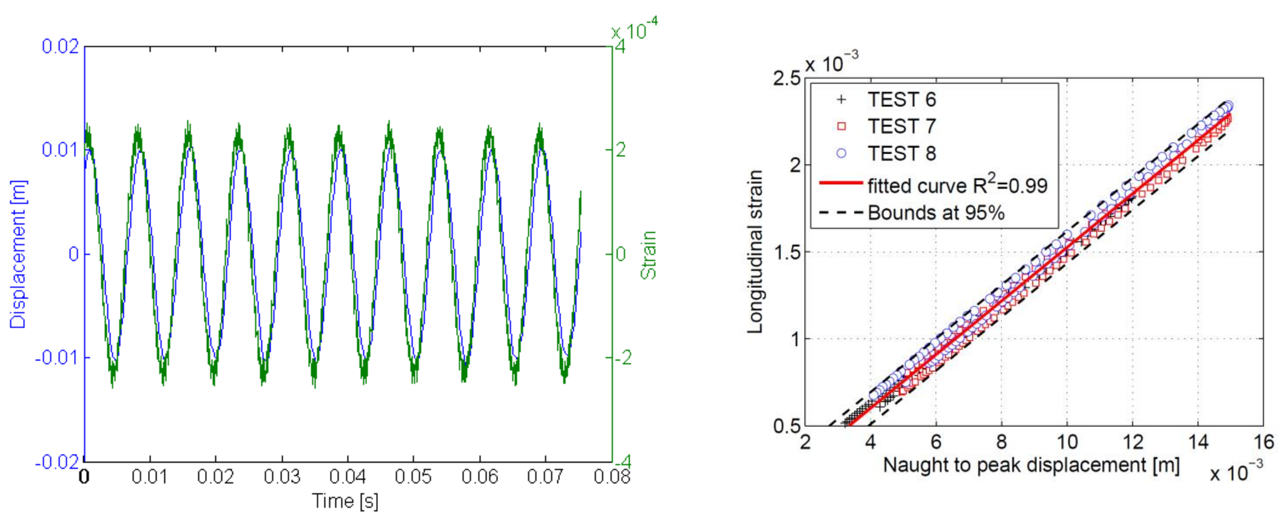


Figure 3 - Process flowchart



(a) (b)

Figure 4 – (a) Displacement (blue) and strain (green) time signals at one vibration amplitude used for the strain-displacement calibration. (b) The linear strain-displacement relationship at different vibration levels.

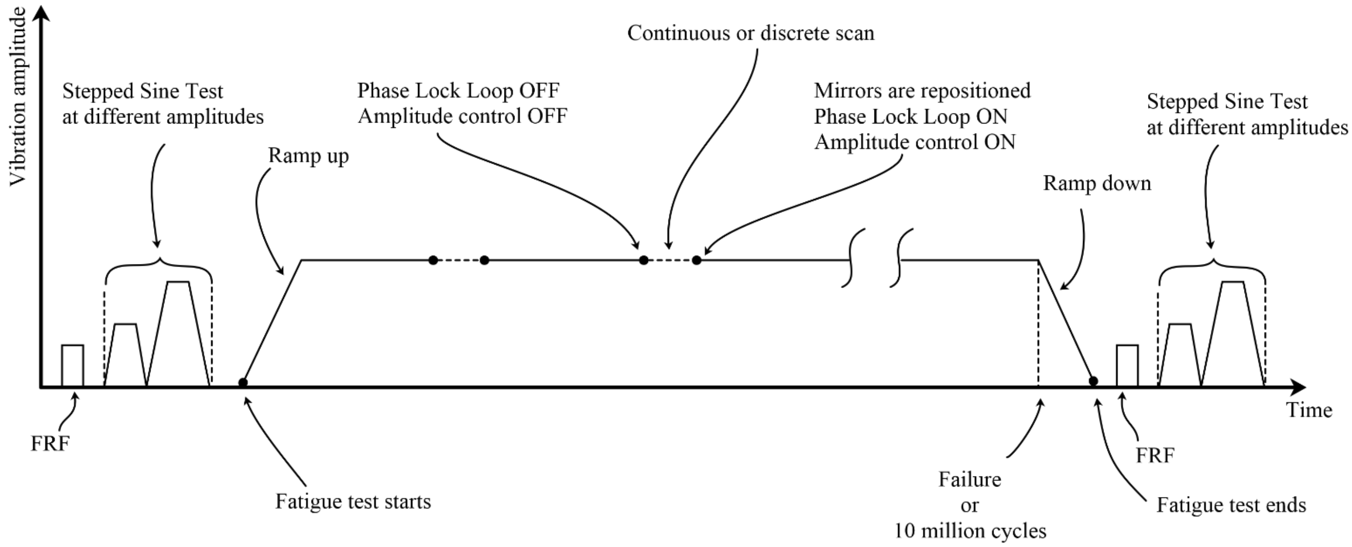


Figure 5 - Time sequence of the software operations

After the stepped sine test, the software saves the strain-displacement relationship to use during the fatigue test. The measured point of the laser is stored and the software requires a grid of points for a discrete scanning and/or the measurement parameters for executing CLSDV measurement technique; this latter requires both the scan rates and amplitudes of the sinusoidal voltages for the X-Y scanning mirrors. The measured area is controlled to be within the measurable range of the LDV.

Referring to Figure 5, when the fatigue test starts, the vibration phase and amplitude are constantly fed back to the software control. The PLL control locks the phase between the input and the output by changing the excitation frequency. As soon as the output phase exceeds an upper and lower threshold spaced apart the target phase, the controller is activated. The amplitude control is based on the same principle. In addition, while the test is running, nonlinear vibrations are monitored. Controls stop working at regular interval in order to allow the ODS measurement, which would capture any changes in ODSs by delamination propagation. When failure criterion is met or 10 million cycles are reached, the fatigue test stops and modal analysis is carried out.

Several specimens were tested with this procedure but only few test data are reported in here. Thanks to the LDV system it was possible to study the evolution of four recordings:

- Resonant frequency decay
- Changes in ODS during the endurance
- Presence of extra harmonics in the response vibration
- Changes in vibration amplitude response before and after the endurance.

3 RESULTS

The damage evolution in fatigue tests can be monitored by measuring the residual stiffness of the component. In a dynamic environment that means to monitor the resonant frequency decay (Figure 6). Further, by capturing the surface temperature of the component, one can correlate the drops in frequency with the delamination initiation and propagation. From Figure 7 one can observe how the temperature could help to identify the damage onset temporally (maximum temperature evolution over number of cycles) and spatially (thermal images).

Test 2 was carried out at low vibration amplitude, its natural frequency never changed. It ran for 10 million cycles without developing damage. This test is considered as benchmark reference for comparisons with failed specimens. The outcomes from the stepped sine test performed before and after fatigue match, since no damage was occurred. The response and the magnitude of the transmissibility are reported in Figure 8. Instead, the other test data present much clearer signs of structural degradation. Referring to Test 3, the resonance frequency dropped by 6% as shown in Figure 9. In addition the nonlinearity got enhanced due to buckling delamination and fretting between delaminated plies.

The modal analysis carried out before and after the endurance proved to be useful for understanding the structural modification that the specimen has undergone. Nevertheless, it does not provide any information about the temporal evolution of the damage and the appearance of nonlinearities.

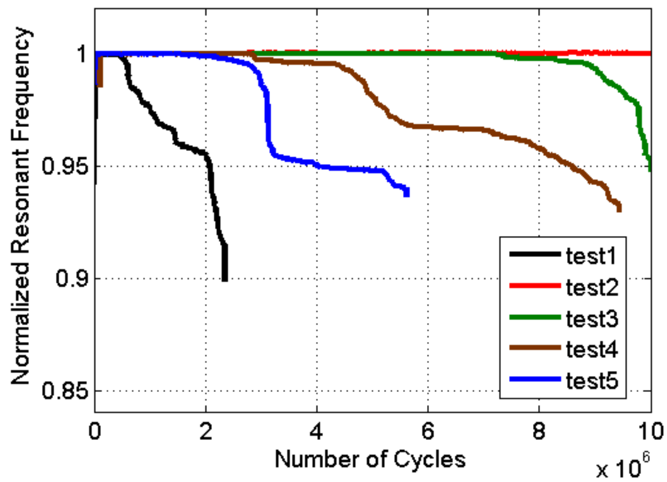
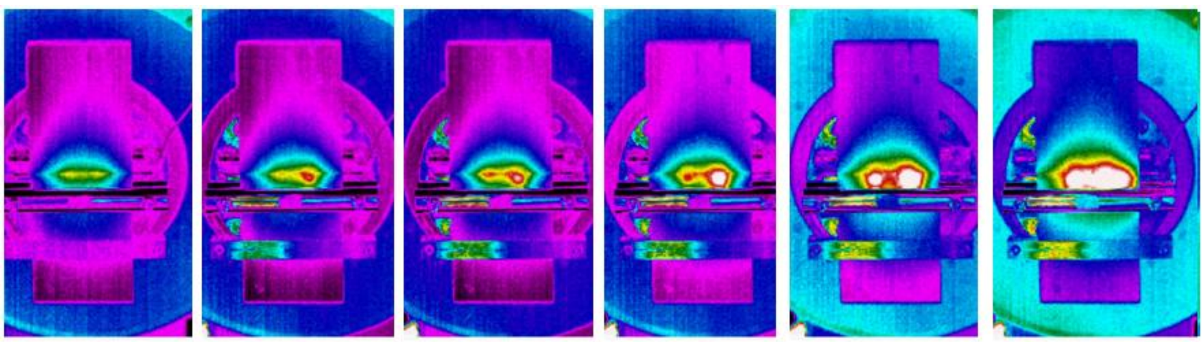
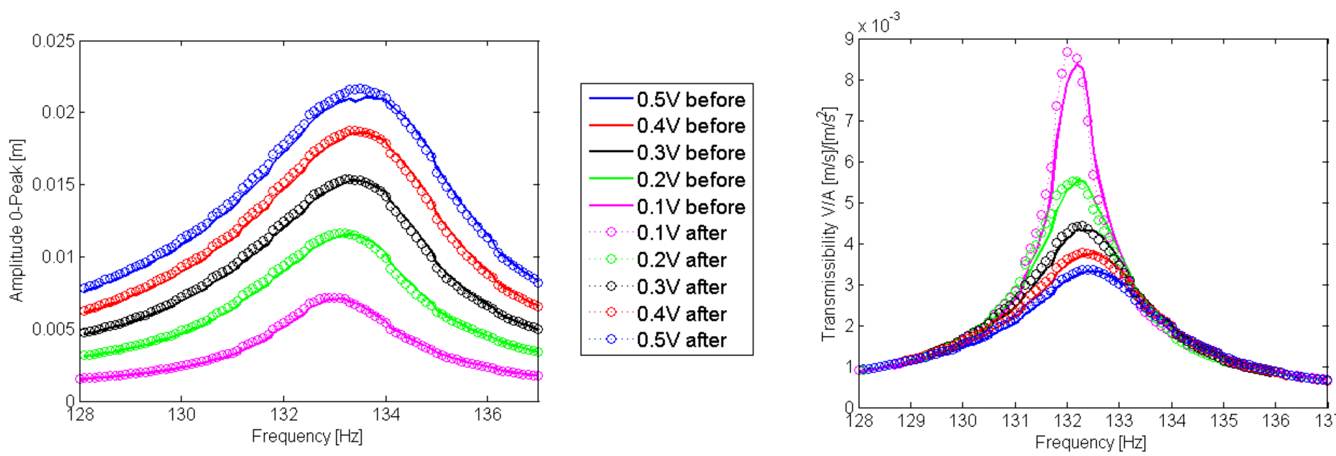


Figure 6 - Compared frequency decays



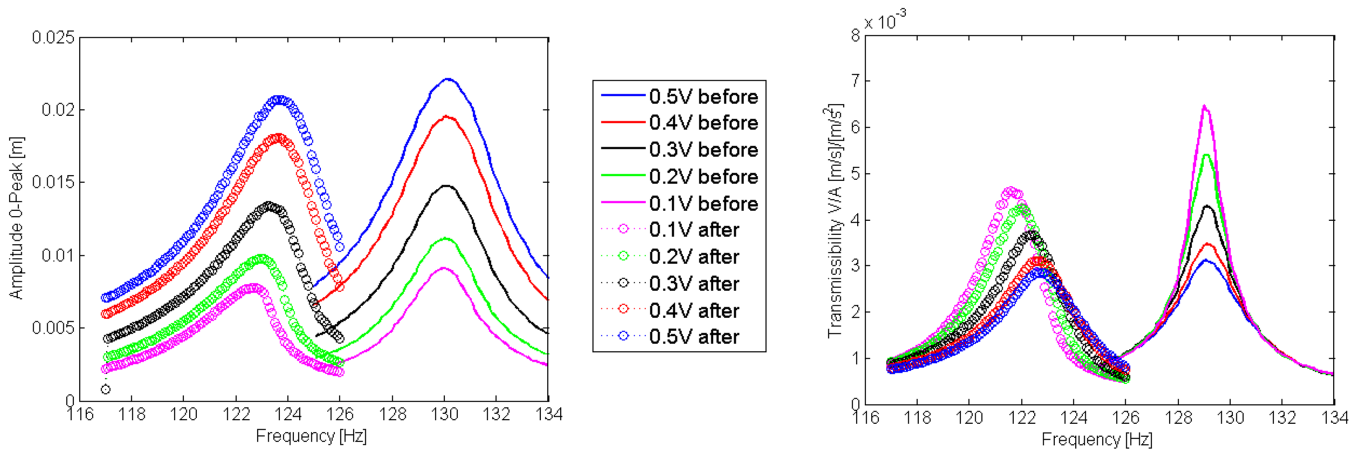
(a) (b) (c) (d) (e) (f)

Figure 7 - Compared temperature profiles for Test 3. (a) 4 (b)7.6 (c) 8 (d) 9 (e) 9.5 (f) 10 million of cycles



(a) (b)

Figure 8 – Response (a) and transmissibility (b) of Test 2 before and after fatigue.



(a) (b)

Figure 9 – Response (a) and transmissibility (b) of Test 3 before and after fatigue.

Measuring the ODSs and controlling the presence of higher harmonics in the response vibration while fatigue testing helps to identify in time the damage evolution. By using the LDV while the PLL and the amplitude control are active, it is possible to gather rapid information about the level of nonlinearity. For the reference test, the presence of higher harmonics was not captured during the 10 million cycles. However, referring to Figure 10 as soon as the first damage occurs, the vibration becomes highly nonlinear, with a second harmonic that increases by 4% after the first drop in frequency at 3 million cycles. After that, as a consequence of delamination propagation, the second harmonic reaches a value 20% higher than its initial value.

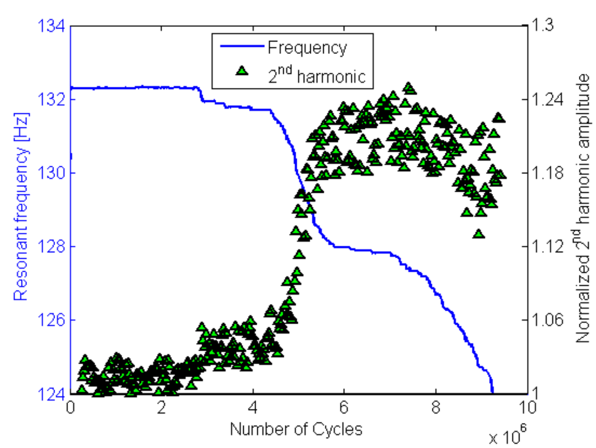


Figure 10 – Increase of the second harmonic of the vibration velocity.

In addition to the nonlinear behaviour, delaminations cause changes in the ODSs. The SLDV scanning performed at regular intervals captured changes of the deflection shape due to developing damages. Referring to Figure 11, it is possible to see how the onset of the delamination in the right side of the specimen causes a torsional movement, changing the target strain field. Thanks to this observation, it was possible to understand that referring the fatigue test to a constant strain after the delamination initiation is misleading.

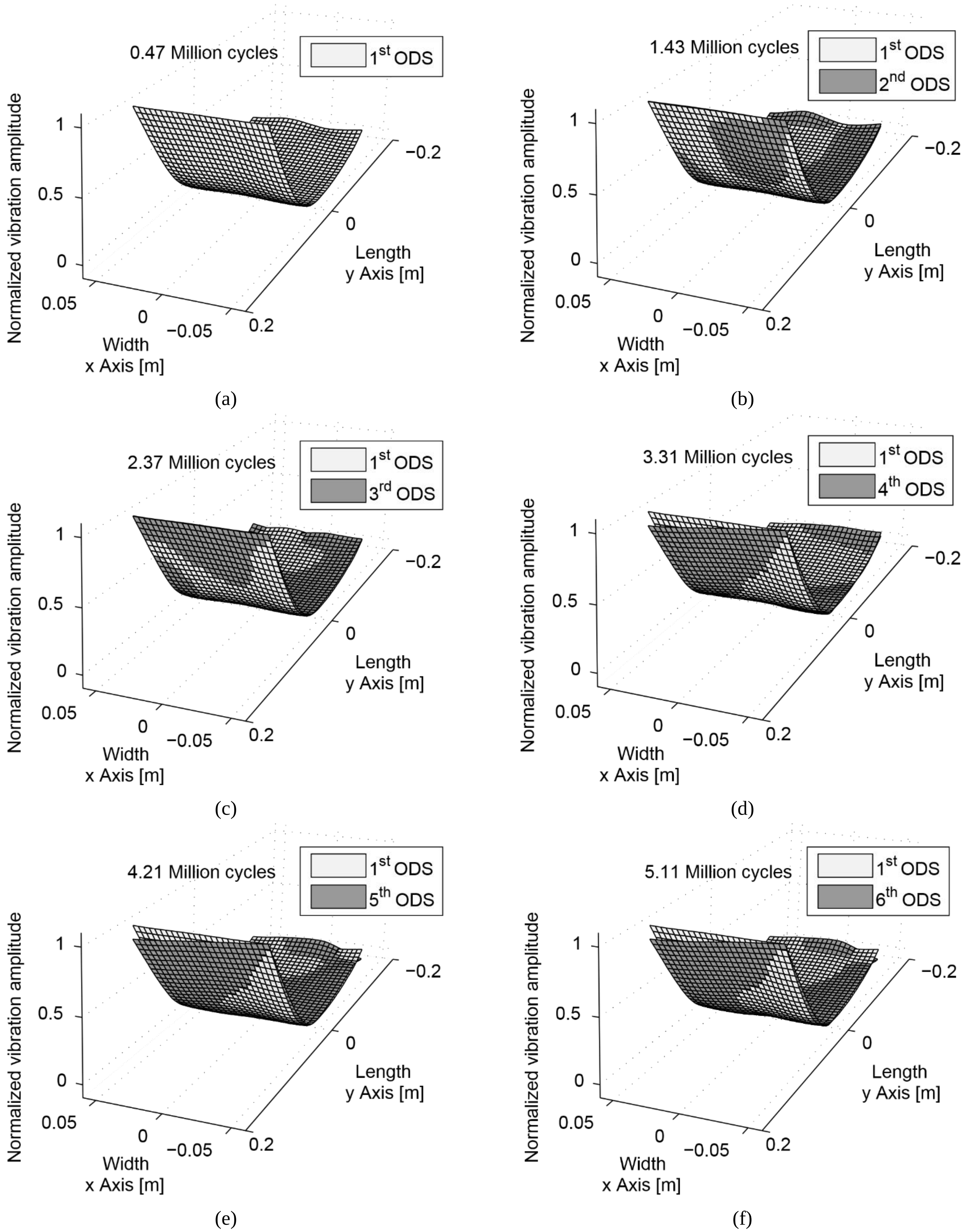


Figure 11 – Time sequence of ODSs for Test 3.

4 CONCLUSIONS

This paper has presented a testing strategy based on SLDV technology for monitoring the fatigue behaviour of composites components under vibratory tests. It is important to say that these tests are executed at large vibration amplitudes, sometimes in the order of 80mm peak to peak. Due to such amplitudes, the SLDV seemed the only measurement technology capable of tackling these levels and, thanks to its contactless feature; SLDV has enabled several different measurement techniques. MONTEVERDI software was designed around such a technology with the intent of fully automating lengthy vibration fatigue tests.

Some of the tests results obtained during an ongoing research programme are presented and discussed in the paper. The composite fatigue behaviour is complex and several parameters are required for understanding the evolution of damage. In this paper, the temperature was shown to be a useful indicator for identifying the damage initiation. Tracing of resonant frequency alongside the acquisition of deflection shapes helps to understand how the damage tends to propagate. Similar signs are given by the mapping of additional nonlinear spectral harmonics, which are caused by the increasing level of damage, from the LDV output signal. Additional information regarding the failure criteria for composites from vibratory conditions are discussed in more details in dedicated composites journals.

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